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DEPENDENCE OF SURFACE RESIDUAL STRESS ON LASER POWER AND LASER SCAN VELOCITY

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1. Introduction

Laser treatment of metals becomes a challenging technique since surface modification is feasible without influencing the bulk properties of a metallic substrate. The beneficial effects of laser surface melting of steels are basically due to a rapid solidification and rapid cooling processes. The cell size obtained is very small, usually in the order of 1 - 10 μm whereas a high density of dislocations in the order of 10^9 - 10^{10} cm^{-2} has been observed as well. In the melting zone, the structure and properties of the material have changed completely and a high internal stress or residual stress has been usually developed. The high residual stresses may cause cracks in the surface layer. After laser surface treatment, the surface stress behaves as in a two dimensional stress state in case a phase transformation in the substrate is absent. The stress varies slightly along the depth.

The surface residual stress is dominated by cooling rate as well as plastic deformation, both of which are related to the temperature profile of the melt pool and the thermophysical properties. Various models of heat flow for the surface melting and solidification have been proposed in the literature [1-5]. Some analytical and numerical solutions about the temperature profile and the cooling rate are available. In this paper the processes of solidification, cooling and plastic deformation have been investigated in order to describe a relationship between the surface residual stress and laser parameters.

In this paper a study is reported on the stress state of laser melted steel, SS 304. In particular a relation between the stress state σ, the laser beam velocity V_b and the laser power P has been derived which is compared with experimental results of surface stresses measured by X-ray techniques.

2. Experiments

In this study a transverse flow Spectra Physics 820 CO_2 laser of 1.5 kW is applied, with a 127 mm ZnSe lens. The sample of SS 304 is mounted on a numerically controlled XY-table. Argon was used as a shielding gas to prevent oxidation. The conditions were 500 W to 1500 W power on the surface, focus point 15 mm above the surface, and a scan velocity ranging from 0.02 to 0.08 m/s. Tracks were made adjacent to each other, 20 in total with 30% overlap. The beam diameter is 0.6 mm.

The stress measurements were carried out using a well aligned Philips X-ray diffraction system (PW1820 equipped with a θ drive). The diffractometer is equipped with a fine focus copper tube operated at 45 kV, 25 mA and a graphite monochromator in the diffracted beam which filtered all radiation except CuKα. Copper radiation was chosen because of the small penetration depth. (Penetration depth at 90% intensity loss, Cu on steel: 5 μm, Cr on steel 10 μm).

The stress σ_ϕ is measured using the $\sin^2\psi$ method [6]

$$\varepsilon_{\psi\phi} = \frac{d_{\psi\phi} - d_0}{d_0} = \frac{(1+\nu)}{E}\sigma_\phi \sin^2\psi, \qquad (1)$$

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where E represents the modulus, ν Poissons ratio, d_0 the strain free [hkl] plane distance, $d_{\psi\phi}$ the strained [hkl] plane distance, ε the strain and σ_ϕ the stress to be determined. For ψ and φ reference is made to fig. 1. The stresses normal to the surface are assumed to be zero. E=220 GPa and ν = 0.3 were used for the stress analysis. Fig. 2 shows the dependence of residual stress σ on the ratio $(V_b/P)^{1/4}$.

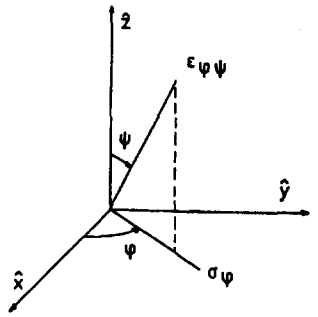

Fig. 1 System and symbols used in the stress measurements.

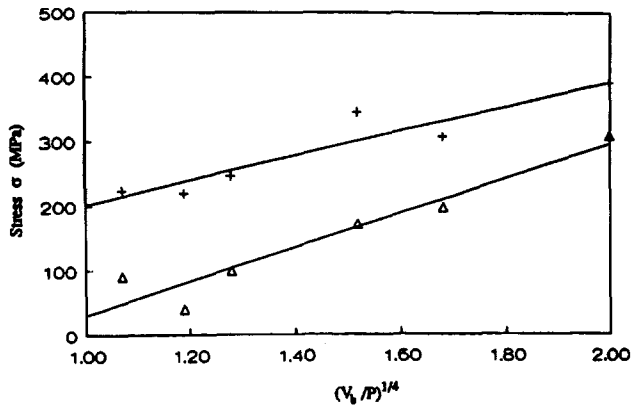

Fig. 2 The dependence of X-ray surface stress on scanning velocity, V_b, and laser power, P.
σ_T - transverse direction to the laser track (+).
σ_L - longitudinal direction to the laser track (Δ).

3. Discussion

In the laser track the internal stresses are induced by the thermal expansion and the plastic flow, and part of them are released by the cooling of the substrate outside of the track. The internal stress may be expressed as follows:

$$\sigma = E\varepsilon,$$

where:

$$\varepsilon = \alpha\Delta T - \varepsilon_p - \varepsilon_c. \tag{2}$$

E represents the elastic modulus, ε is the effective elastic strain, ε_p is the plastic strain, whereas ε_c is the strain released by the cooling of the substrate outside the laser track. α is the thermal expansion coefficient and ΔT is the variation in temperature. The strain ε_c released by the cooling of the substrate outside of the laser track is related to the temperature profile and cooling rate. In the following it is assumed that at high temperature, the plastic strain dominates the process, whereas at low temperature, most of the thermal expansion is released by the cooling of the substrate of the laser track.

The typical surface stress in the laser track measured by X ray diffraction ranges from 100 MPa to 500 MPa and is much smaller than the thermal stress $\sigma = E\,\alpha(T_m - T_0) \approx 1200$ MPa if all of the thermal expansion were quenched to room temperature. Therefore, most of the thermal expansion is released by the plastic flow as well as by the substrate cooling outside of the laser track.

From heat modelling of the molten pool of the laser track, the cooling rate is generally proportional to the square or cubic power of the temperature difference to room temperature, and decreases rapidly with decreasing temperature. Therefore, the thermal expansion αΔT in the laser track is mainly released by plastic flow at higher temperature. The following basic assumptions are made :

- The laser track is treated as a fixed thin plate (x-y plane). There is no temperature gradient along the z-axis. Further it is assumed that there is no stress developed in the plate before it has completely resolidified because liquid flow above the melting point T_m is so quick that no internal stress could remain in the plate. After the centre of the plate cools below the melting point, an internal stress may be induced by the thermal expansion.
- There are no cracks generated in the plate during cooling. It means that all the thermal expansion would be converted to the plastic flow and elastic strain. Eq.(2) can be applied in this process.
- All the properties of the material except the elastic modulus are independent of the temperature. The dependence of the elastic modulus E with temperature T is suppose to be given by:

$$\frac{E}{E_0} \approx 1 + \frac{1}{E_o}\left(\frac{dE}{dT}\right)\Delta T, \tag{3}$$

where E_0 is the elastic modulus at room temperature T_0.

Because there is a temperature distribution along the y-axis perpendicular to the laser scan direction, the cooling rate and the plastic flow will vary along the y-axis within a certain period of time. This makes the analysis very complex. To arrive at an analytical solution of eq. 2. a further simplification is needed assuming that the plate maintains a homogeneous temperature along the y-axis during cooling. The cooling rate is still represented by the heat model of laser treatment. Then ε_p in eq. (2) may be expressed as follows:

$$\varepsilon_p = \int\left(\frac{\dot{\varepsilon}_p}{\Phi}\right)dT, \tag{4}$$

where $\dot{\varepsilon}_p$ is the plastic strain rate and Φ is the cooling rate. Taking the laser beam as a line source the cooling rate can be written as [7]:

$$\Phi = \frac{2\pi\kappa V_b}{P}(T - T_o)^2, \tag{5}$$

where P is the absorbed power and κ represents the thermal conductivity.

The growth rate/solidification rate V_s depends on V_b according to [8]:

$$V_s = \sqrt{\left(\frac{2\pi V_b}{P\Delta h_f}\right)}\kappa(T_m - T_o), \tag{6}$$

where Δh_f is the latent heat per volume and T_m is the melting temperature. Since the eutectic spacing d is found to be related to the solidification rate by d^2V_s = constant, the eutectic spacing can be described as:

$$d = \beta\left(\frac{P\Delta h_f}{2\pi V_b \kappa^2}\right)^{\frac{1}{4}}\frac{1}{\sqrt{(T_m - T_o)}}, \tag{7}$$

where β is a constant which can be experimentally determined by measuring d.

At high temperature diffusional flow of point defects leads to the Newtonian-viscous creep of the polycrystalline material. This transport produces creep under a stress σ:

$$\dot{\varepsilon} = \gamma\frac{D_v}{d^3}\frac{\sigma\Omega}{kT} \tag{8}$$

where D_v is the coefficient of volume diffusion, Ω is the atomic volume, and the constant γ is in the order of 10. In eq.(8) the factor $\sigma\Omega/kT$ represents the amount of work done when a point defect is produced under a stress, thereby changing the local saturation of point defects. It is quite clear that when boundary diffusion dominates D_v should be replaced by $\delta D_b / d$, where δ represents the effective cross section of a boundary for diffusional transport. The former situation is called Nabarro-Herring creep, whereas the latter is known as Coble creep [9]. Substitution of eq.(5) and of eq.(7) into eq.(8) and eq.(4) yields:

$$\varepsilon = f(T)\left(\frac{P}{V_b}\right)^m \sigma, \tag{9}$$

where m is equal to $\frac{1}{2}$ assuming volume diffusion or $\frac{1}{4}$ in case that boundary diffusion is the most dominant mechanism. The factor f can be expressed in terms of the various parameters [9].

Eq. (9) indicates that the surface residual stress is proportional either to $(V_b/P)^{1/4}$ or to $(V_b/P)^{1/2}$. In fig. 2 the stresses parallel to the scan direction (σ_L) and transverse to the laser scan direction (σ_T) are plotted. It suggests that the diffusional flow resulted from flow of point defects around boundaries is the predominant process of plastic flow at high temperature in the laser treated material.

4. Conclusion

A relation between the stress state σ and the laser beam velocity V_b and the laser power P has been derived assuming an eutectic composition and a line source of laser beam. It turned out that σ scales with $(V_b/P)^m$ where m is ranging between $\frac{1}{4}$ and $\frac{1}{2}$. The experimental results of surface stresses measured by X-ray suggest that $m = \frac{1}{4}$ is more appropriate indicating that the plastic flow is dominated by diffusional flow of point defects along boundaries instead of volume diffusion through the bulk.

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